Influence Evaluation of Wheel Surface Profile on Traversability of Planetary Rovers

Masataku Sutoh, Tsuyoshi Ito, Keiji Nagatani, and Kazuya Yoshida

***Abstract*— Planetary rovers play a significant role in surface explorations on the Moon and/or Mars. However, because of wheel slippage, the wheels of planetary rovers can get stuck in loose soil, and the exploration mission may fail because of this situation. To avoid slippage and increase the wheels' drawbar pull, the wheels of planetary rovers typically have parallel fins called lugs on their surface. In this study, we conducted experiments using two-wheeled testbeds in a sandbox to provide a quantitative confirmation of the influence of lugs on the traversability of planetary rovers. In this paper, we report the results of the experiments, and discuss the influence of lugs on the traversability of planetary rovers.**

I. INTRODUCTION

During NASA's surface explorations on Mars, mobile robots (rovers) played a significant role in geological investigations. In future missions, lunar and planetary rovers are also expected to have good performances for geological investigations. However, the surface of the Moon and/or Mars is covered with loose soil, and there are numerous steep slopes along the rims of craters. Under such conditions, wheeled rovers can get stuck and, in the worst case scenario, such problems can result in the failure of the mission (see Fig.1).

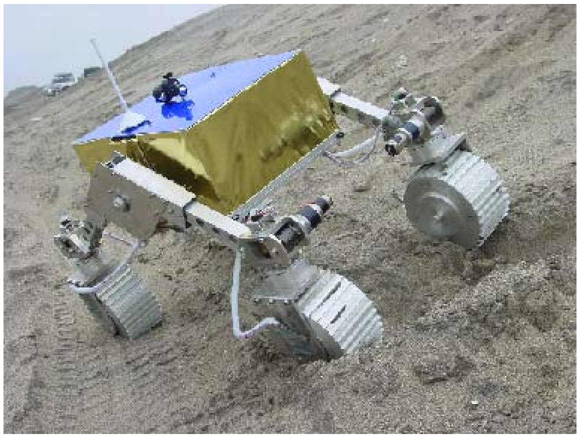

Fig. 1. Stuck rover testbed in loose soil

In order to avoid such problems, many research groups have studied the traveling performance of wheeled rovers on the basis of terramechanics [1]-[5]. This is a branch of mechanics that examines the interaction between soil and locomotion mechanisms on loose soil, which was systematized by M. G. Bekker and J. K. Wong in the 1970s [6][7]. Recently, our research group has also been studying the traveling performance of wheeled rovers on the basis of terramechanics [8]-[12].

In terramechanics, the drawbar pull of a wheel is calculated by the normal and shear stresses under the wheel [7]. Typically, the wheels of planetary rovers are equipped with parallel fins called "lugs" on their surface to increase their drawbar pull on loose soil. However, in basic terramechanics models, the drawbar pull for the wheel is derived by estimating the shear deformation modulus instead of considering each lug's effect, and it is difficult to design lugs based on this approach.

There are some works on terramechanics that take into consideration the lugs' effect. K. P. Pandey studied the influence of wheel width and lug length on the wheel's performance. However, the study utilized large target vehicles, such as dump trucks, and we believe that their behavior differs from that of small-sized planetary rovers [13]. K. Iizuka et al. reported experiments using small vehicles such as planetary rovers and wheels with lugs. However, they did not evaluate the influence of lugs on the traveling performance of the wheel mechanism [14]. We did not find any other papers that focus on the effect of lugs for small-sized vehicles. Furthermore, we did not know the suitable length, width, and interval for lugs.

Therefore, in this study, we first performed experiments to evaluate the influence of the number of lugs on the traveling performance of planetary rovers on loose soil. In these experiments, we measured the slip ratio of the wheels in a sandbox with different drawbar pulls for wheels and different numbers of lugs. Secondly, we performed experiments with a small number of lugs to evaluate a single lug's effect of generating traction force. In this paper, we introduce the above-mentioned experiments, and report the results and discussions.

II. EVALUATION OF INFLUENCE OF NUMBER OF LUGS ON TRAVELING PERFORMANCE

In this study, we performed traction tests using a two-wheeled testbed with different types of wheels to evaluate the influence of lugs on the traveling performance. In this section, the experimental setup and results are reported in detail.

A. *Evaluation Method*

To evaluate the traveling performance of wheels, we adopted the slip ratio according to the drawbar pull as an

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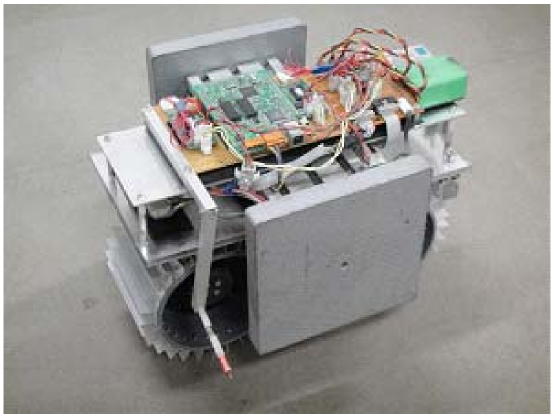


Fig. 2. Two-wheeled testbed

(a) No lugs (b) 5 lugs (c) 30 lugs

(d) 45 lugs (e) 60 lugs (f) Infinite lugs

Fig. 3. Wheels with different numbers of lugs

indicator. The slip ratio s is defined as [7]

$$s = \frac{r\omega - v_x}{r\omega} = 1 - \frac{v_x}{r\omega} \tag{1}$$

where v_x denotes the longitudinal traveling velocity and $r\omega$ denotes the circumference velocity of the wheel. In this equation, the slip ratio takes a value between 0 and 1. When the wheel moves forward without slippage, the slip ratio is 0; when the wheel does not move forward at all because of slippage, the slip ratio is 1. Therefore, a smaller slip ratio for a drawbar pull denotes a high traveling performance according to this definition.

B. Experimental Setup

1) Target Testbed: In this study, we developed a small two-wheeled testbed with interchangeable wheels. Fig. 2 depicts an overview of the testbed. The wheel has a diameter of 144 mm and a width of 100 mm; each lug has a length of 14 mm. That is, the wheel has a diameter of 172 mm, including the lug lengths. We utilized different numbers of lugs, as shown in Fig. 3. The wheel shown in Fig. 3 (f) differs from other wheels. This wheel is the wheel shown in 3 (c) covered with sandpaper. This implies that the number of lugs is infinitely large. To align the testbed weight to 10.4 kg for all the different wheels, we used additional weights.

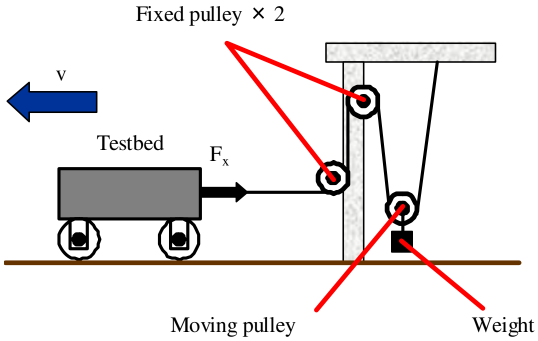


Fig. 4. Experimental system

2) Traction Apparatus: Pulling a weight apparatus is a simple way to load the variable traction force for wheels. However, to maintain sufficient travel distance for a rover testbed, a sufficient height is required for the stroke of a weight by using a single fixed pulley. To double the travel distance, we developed a traction apparatus consisting of one moving pulley and two fixed pulleys (see Fig. 4). Traction tests can be performed with different drawbar pulls by replacing a weight on the moving pulley. In this case, a half mass of the weight on the moving pulley is the drawbar pull required for the testbed.

3) Target Soil: Each experiment was performed in our sandbox, which was covered with a Regolith simulant. The Regolith simulant is a soil that simulates the mechanical characteristics of the lunar soil. The sandbox had a length of 95 cm, a width of 40 cm, and a depth of 20 cm

C. Experimental Conditions

In these traction tests, we changed the weight on the traction apparatus for each wheel type illustrated in Fig. 3. The weights were set at increments of 0.4 kg up to 3.4 kg. The wheel velocity v was fixed at 1 cm/s in all the experiments. To obtain the slip ratio, we measured the time for the testbed to travel 35 cm after the sinkage of the wheels stopped. We conducted three trials for each condition.

D. Experimental Results

The experimental results for the six types of wheels are plotted on the graph depicted in Fig. 5. In accordance with the figure, the larger the number of lugs, the smaller is the slip ratio. This implies that a large number of lugs contributes to a high traveling performance; this is a predictable consequence. Furthermore, the traveling performance decreases from the wheel with 60 lugs to the wheel with infinite lugs.

Fig. 6 presents a comparison graph, extracted from Fig. 5, for wheels with a large number of lugs. According to the figure, the improvement in the traveling performance from the wheel with 30 lugs to the wheel with 45 lugs is not large, and the traveling performance decreases from the wheel with 45 lugs to the wheel with 60 lugs. This trend corresponds to the above-mentioned results of the wheel with infinite lugs. From this result, we predict that there is an optimum number

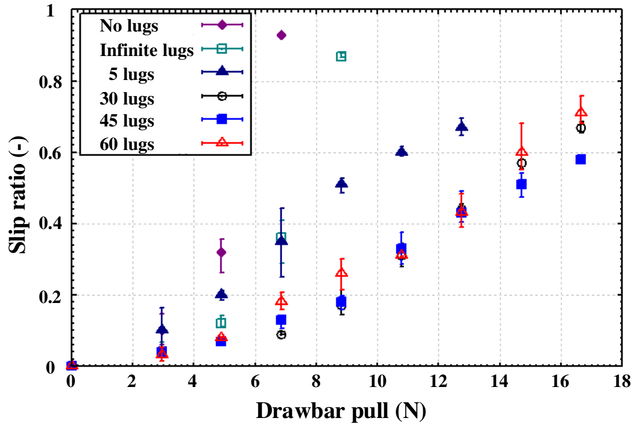


Fig. 5. Drawbar pull vs. slip ratio (Entire data)

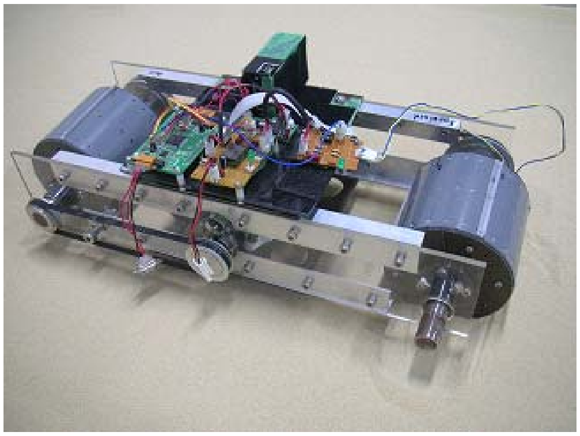


Fig. 7. Improved two-wheeled testbed

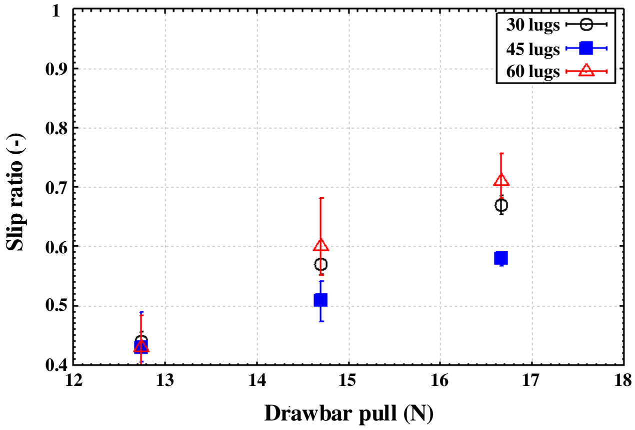


Fig. 6. Drawbar pull vs. slip ratio (Wheels with large numbers of lugs)

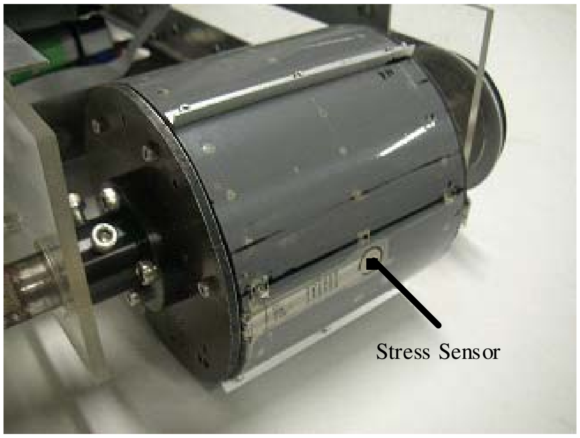


Fig. 8. Stress sensor on the front wheel of the testbed

of lugs for the wheel. Furthermore, we understand that the lugs' effect of generating traction force is much larger than our expectation. Given this, a detailed understanding of the lugs' effect is required.

In these experiments, we observed an interesting phenomenon: the testbed alternately moved forward and got stuck when the number of lugs was small. Therefore, we considered that a single lug's effect of generating traction force can be observed by using wheels with a small number of lugs. In this context, we performed the experiments discussed in the next section.

III. EVALUATION OF A SINGLE LUG'S EFFECT OF GENERATING TRACTION FORCE

To discuss a single lug's effect of generating traction force, we performed slope climbing tests using a two-wheeled testbed with wheels having a small number of lugs. In this section, the experimental setup and results are reported in detail.

A. Evaluation Method

In terramechanics, the drawbar pull of a wheel is calculated by the normal and shear stresses under the wheel; the shear stress depends on the normal stress. Therefore, to evaluate a single lug's effect of generating traction force from the point of view of terramechanics, we measured the normal stress under the wheel and the traveling velocity of the testbed as indicators.

B. Experimental Setup

In this study, we developed a two-wheeled testbed, which is an improved version of the testbed presented in the previous section. Fig. 7 depicts an overview of the testbed. The wheel has a diameter of 114 mm and a width of 100 mm, and each lug has a length of 5 mm. That is, the wheel has a diameter of 124 mm, including the lug lengths. To align the testbed weight to 4 kg for all the different wheels, we utilized additional weights. The normal stress under the wheel was obtained online by the FlexiForce button sensor (A201; Nitta Corp.) mounted on the surface of the front wheel of the testbed (see Fig. 8). The thickness and diameter of the sensor are 0.819 mm and 9.5 mm, respectively. The actual traveling velocity of the testbed is obtained by a position estimation device with optical sensor and laser sources, mounted on the testbed [15].

Each experiment was performed in our sandbox, which

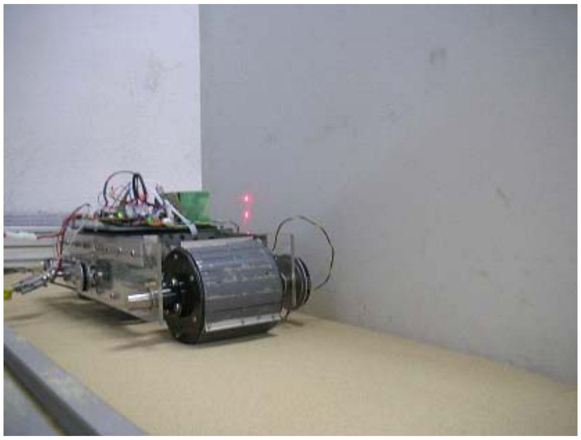


Fig. 9. Experimental overview

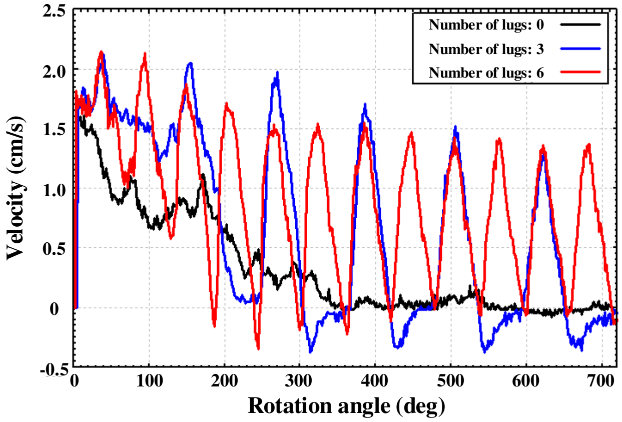


Fig. 10. Rotation angle of wheel vs. traveling velocity

was covered with Toyoura sand. The sandbox had a length of 2 m, a width of 1 m, and a depth of 15 cm.

C. *Experimental Conditions*

In these slope climbing tests, the sandbox was manually inclined to change its slope angle. We set the slope angle at 4°. We conducted three trials for the three types of wheels: those with no lugs, those with 3 lugs, and those with 6 lugs. We measured the testbed's actual traveling velocity and normal stress under the wheel. The wheel velocity v was fixed at 2 cm/s in all the experiments (see Fig. 9).

D. *Experimental Results*

The relationship between the rotation angle of the wheel and the traveling velocity are plotted in the graph shown in Fig. 10. From the figure, in the case of a wheel without lugs, the traveling velocity became smaller according to the rotation angle of the wheel. This implies that the wheel started to slip and finally got stuck. In cases of wheels with 3 and 6 lugs, the traveling velocities change periodically. This corresponds to our observation that the testbed alternately moved forward and got stuck. Furthermore, the traveling velocities change in cycles of 120° and 60°. The cycles correspond to the intervals of the lugs on the wheels.

Fig. 11 shows photographs of wheel sinkage for different wheels and Fig. 12 shows a change of the testbed's traveling velocity along with the normal stress under the wheel. It was converted from Fig. 10 by redefining the wheel coordinate that has the vertical downward direction of the wheel as the origin and the forward direction of the wheel as the positive. From Fig. 12 (b) and (c), we found an interesting phenomenon: in the cases of wheels with 3 and 6 lugs, the change in the traveling velocity appears to begin at angles of around 45° and 60°, respectively. These angles are the entry angles of the wheels, where a lug starts to contact the ground, as observed from Fig. 11 (b) and (c). If the lug's effect of generating traction force changes with the normal stress like shear stress, the traveling velocity would also change with normal stress. However, at the angle where a lug starts to contact the ground, although the change in the traveling velocity begins, there is no normal stress under the wheel. From this result, we concluded that the lug's effect has no relation to the normal stress and the lug's effect of generating traction force is more dominant in the traveling performance of the wheel mechanism than the stress under the wheel.

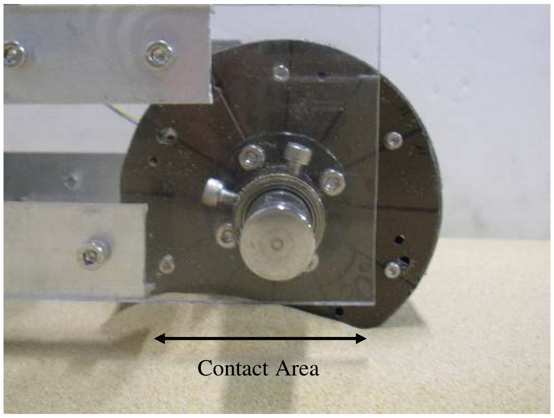
To summarize the above discussion, in the case of wheels with lugs, the change in the traveling velocity is caused by the traction force generated by lugs and the lug's effect of generating traction force has no relation to the normal stress distribution under the wheel. Furthermore, the lug's effect has more impact on the traveling performance than stress distribution does. This result indicates that the drawbar pull of the wheel with lugs cannot be derived from the normal and shear stresses under the wheel as in the terramechanics models, at least in the case of small-sized vehicles. We believe that a new terramechanics model is required to obtain a more reasonable estimation of the traveling performance of the wheel mechanism.

IV. CONCLUSIONS AND FUTURE WORK

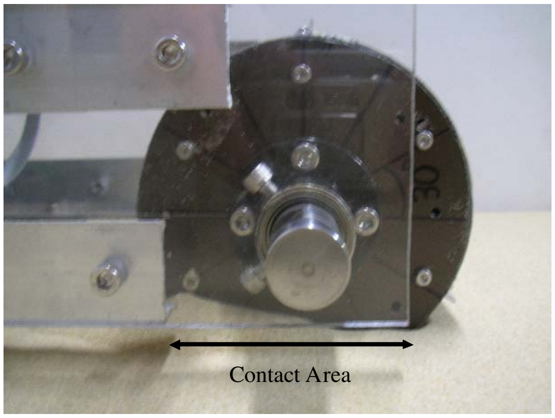
A. *Conclusions*

In this study, two-wheeled testbed experiments were performed for wheels with different numbers of lugs. On the basis of the experimental results on the influence of the number of lugs on traveling performance, we concluded that the increase in the number of lugs on wheels contributes to a high traveling performance.

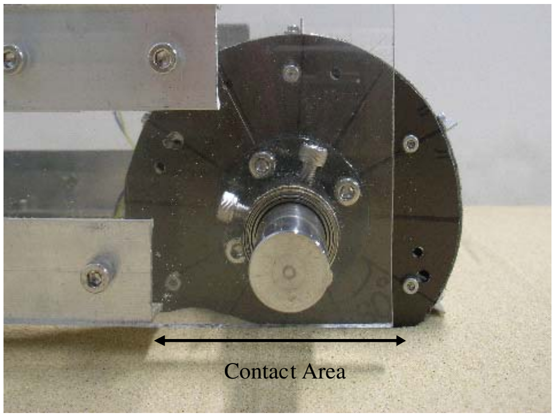
According to the experimental results on a single lug's effect of generating traction force, the lug's effect has no relation to the normal stress distribution under the wheel. Therefore, we concluded that the drawbar pull of wheels with lugs cannot be derived from the normal and shear stresses under the wheel as in the terramechanics models. Furthermore, the lug's effect has a greater effect on the traveling performance of the wheel mechanism than the stress distribution.



(a) Number of lugs: 0

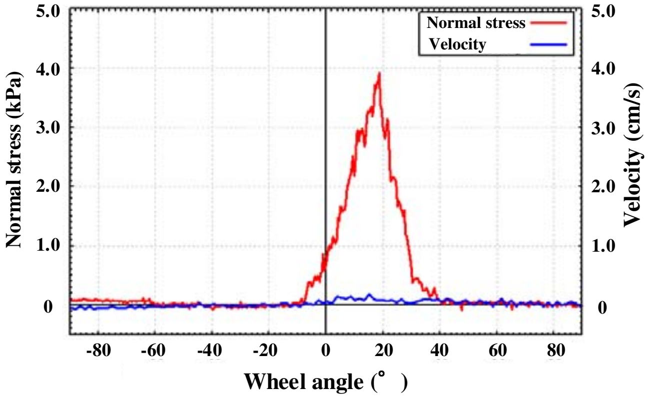


(b) Number of lugs: 3

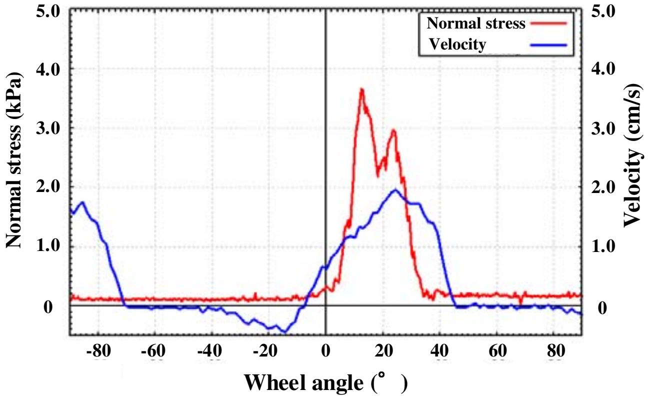


(c) Number of lugs: 6

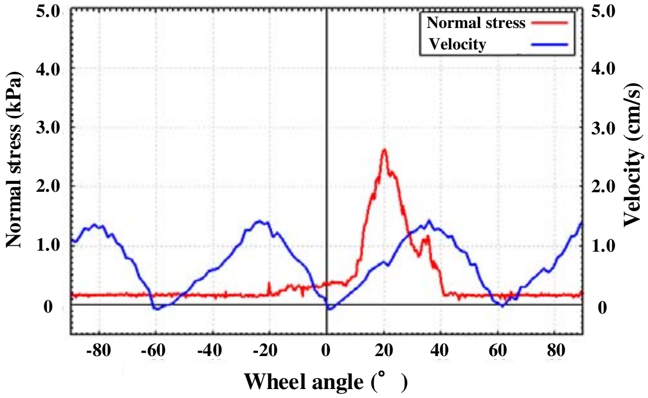
Fig. 11. Wheel sinkage



(a) Number of lugs: 0



(b) Number of lugs: 3



(c) Number of lugs: 6

Fig. 12. Wheel angle vs. normal stress, traveling velocity

B. Future Work

In our future studies, in addition to examining the interval of lugs, we plan to investigate suitable lug length and width through further experiments. The reconstruction of a terramechanics model is another important matter reserved for future work.

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